BELLCOMM, INC.

SUBJECT: An Analysis of Failure Effects in the Lunar Excursion Module Reaction Control System - Case 130

DATE: September 13, 1965

FROM: R. R. Schreib

ABSTRACT

In the LEM as currently configured, loss of a single X axis RCS thruster would necessitate mission abort, since loss of one additional thruster could be catastrophic. The LEM RCS system uses 16 thrusters, mounted as four equally spaced quads, each containing two X thrusters, and one Y and one Z thruster. In each quad, independent but interconnected fuel systems supply an X thruster paired with a Y or Z thruster. An X thruster may be lost by direct failure or by a failure of a paired Y or Z thruster which necessitates fuel shutoff to the pair. In either circumstance, mission abort is necessary because certain other single thruster failures could lead to loss of attitude control.

MSC and GAEC have recognized this problem for some time and are working to provide a detection system to permit timely recognition of and response to thruster and other RCS failures.

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MEMORANDUM FOR FILE

Introduction

This memorandum presents the results of a study conducted in response to the following action item:

> "Investigate report that failure of one (LEM) RCS thruster would require mission abort."

The critical thruster failures in the LEM RCS are first identified using a thruster utilization matrix. This is followed by a qualitative assessment of the impact of these critical failures during the various phases of the LEM mission. Possible alternate methods of control are discussed briefly and the current status of a LEM RCS failure detection system is reviewed. Finally, recommendations are presented concerning the identification of failure detection system requirements and the implementation of such a system.

Problem Definition

The functional requirements of the LEM RCS include orientation, translation maneuvers, thrust vector misalignment compensation, propellant settling impulses, and fine and coarse limit cycle operation for attitude hold. The system is in intermittent use during descent, ascent, and the rendezvous and docking maneuvers.

The LEM RCS uses sixteen 100 lbF thrusters distributed in four equally spaced quads as illustrated in Figure 1. The thrusters are divided equally between two independent but interconnected propellant supply systems indicated in Figure 1 by the System A and System B designation. In addition, these two systems have a crossfeed connection with the main ascent propellant tanks. Each propellant supply system feeds two thrusters in each quad: one X thruster and one Y or Z thruster. Propellant valves are located upstream from each pair of thrusters for use in isolating failed thrusters.

Two categories of failures must be considered: those involving one or the other of the independent supply systems and those involving individual thrusters. Supply system failures due to blockage, leakage, or rupture lead to loss of propellant and loss of all the thrusters in one system.

Loss of thrust from individual thrusters is of primary interest here. Thrust loss from a single thruster can result from a direct failure to fire or indirectly due to manual activation of the propellant valves to isolate other failures. Manual isolation would result in the loss of two thrusters. Failure modes would include failure open or closed of the thrust chamber propellant valves, valve leakage, or mechanical damage to the valves. In addition, failures in the RCS Control System, including the thruster select logic, can result in possible isolation of thrusters.

The LEM RCS thruster utilization matrix of Table 1, derived from Figure 1, illustrates the utilization of the 16 thrusters in obtaining various motions and also the distribution of thrusters between the two supply systems. Table 1 shows that the failure of particular pairs of X direction thrusters would result in loss of rotational control about axes through diagonally opposite thruster quads. In light of the program requirement (1) that no single failure shall, in the event of a second failure in the same area, prevent a successful abort of the mission, it follows that the failure of a single X thruster would be critical and cause for abort before the failure of a second thruster. Further, because of the pairing of each X thruster with one of the Y or Z thrusters through a single isolation valve, the failure on of a Y or Z thruster and its subsequent isolation along with an X thruster would also be cause for abort. Table 1 also shows that $\pm$Y and $\pm$Z translations are also critically dependent on only two thrusters. Further, +Y and -Y translations are dependent upon two thrusters in the same propellant supply system.

The loss of half the thrusters (i.e., one of the two propellant supply systems) results in the loss of pure* Z translation, one Y translational direction, and degraded rotational control about the diagonal axes.

In summary, the critical individual thruster failure modes and the remaining control capabilities which are dependent on the continued operation of a single thruster are:

(1) loss of X thruster and rotational control about diagonal axes due to:

(a) direct failure of X thruster,

(b) isolation with a failed Y or Z thruster;

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*Pure meaning translation without a rotational component or rotation without a translational component.

(2) loss of Y or Z thruster and Y or Z translation control due to:

(a) direct failure of Y or Z thruster,

(b) isolation with a failed X thruster.

The loss of eight thrusters due to a propellant supply system failure results in:

(1) diagonal axis rotational control and $\pm$Z axis translation being dependent on single thruster operation, and

(2) a total loss of +Y or -Y axis translation control capability.

Impact of RCS Failures on the Mission

Control about axes in the Y-Z plane, including the diagonal axes between quads, is particularly important during ascent when ascent engine thrust misalignment must be counteracted by the RCS. Normally, the thrusters are used in pairs to produce rotational control about these axes, but during ascent the use of single X thrusters to correct attitude also contributes to the available ΔV capability.

During descent, compensation for the offset center of gravity in thrust vector misalignment is realized by gimballing the descent engine. The gimballing rate (0.2°/sec) is too small to act as an effective control torque if two X thrusters should fail and any sizable disturbing torque is introduced.

No less important is the fact that the LEM capability to complete active rendezvous and docking is degraded without full attitude control. The CSM does have a rescue capability which could be used in the event of LEM RCS translation failures; however, it is not clear that docking could be effected by the CSM if the LEM has lost rotational control capability.

The failure of any thruster closed at any time leads to degraded control and the inefficient use of propellants. An uncorrected failure open at any time leads to an accelerated rate of propellant usage. Two types of propellant loss failures in a single system can greatly degrade performance. One is the loss of propellant from one of the independent supply systems due to failure closed or blockage of the main shutoff valve, rupture of the tank, or less likely, failure closed of the pressurization section which is parallel/series redundant. In this case the isolation valves are of no value. The other type is a failure in the manifold section downstream of the shutoff valve resulting in loss of all eight thrusters. If the failure is detected, it may be possible to save the propellants. These failures and their impact have been identified in the Apollo Mission Planning Task Force (AMPTF) Contingency Analysis for the LEM. (2)

Another AMPTF study (3) indicates that RCS propellant loadings are more than adequate for a worst nominal mission and meet abort mission requirements in the event of a single system failure if a CSM rescue capability is available.

Depending on the final configuration of the primary LEM guidance system, a detection system may be required to provide RCS thruster failure information to the guidance and control system. For example, MIT incorporates a prediction model in the guidance programming that infers vehicle angular rate from a knowledge of vehicle dynamic behavior and thruster firing commands. It has been shown that unidentified thruster failures can affect adversely the estimate of the rate and the descent engine's moment offset to such an extent that the control system diverges and large attitude errors result. If thruster failures are detected, the thruster select logic and the prediction model could be adjusted to maintain control.

To summarize the impact of these failures, it is clear that the loss of a Y thruster for any reason, and the failure of a Y or Z thruster on, and the associated "isolation" loss of an X thruster, would be cause for mission abort. The failure off of a Y or Z thruster (i.e., without requiring isolation and loss of an X thruster) is less serious since the subsequent loss of another specific thruster would result only in the loss of translation control in Y or Z. While it is not clear that loss of this latter capability could result in crew loss, it is nevertheless a serious loss.

Alternate Control Methods

There are several alternate sources of control torques which might be considered as backup control methods. The first uses the fact that the center of gravity of the LEM is always in or below the plane of the thruster quads. Ignoring the minor (usually < 1") displacement from the X axis, the center of gravity moves in a +X direction from station 188 at LEM/CSM separation to 218 at lunar touchdown, to 244 at lunar launch, to 254 at completion of docking*(4). The latter station is in the quad plane.

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*Values for 32,000 lb LEM

These displacements provide a moment arm about the center of gravity for thrusters in the YZ plane of from approximately 5 1/2 feet to 3 feet during descent and from less than one foot to zero during ascent. By firing the Y and Z thrusters in a quad, torques of from 770 to 420 ft.lbF could be developed about the diagonal axes during descent. (The nominal coupled jet torque is 1100 ft.lbF.) The maximum torque during ascent would be 140 ft.lbF, falling to zero at docking. These motions do not provide pure rotation, of course.

Gyroscopic coupling effects could be utilized to obtain some small amount of roll control about the diagonal axes. Simultaneous pitch and yaw motion would counteract unwanted roll motion, for example. Unfortunately, the coupling terms involve differences of LEM moments of inertia which are numerically similar and the resulting effect is more than an order of magnitude less than that of coupled thrusters. "Spin stabilizing" the LEM about the X axis during ascent in the event of loss of control thrusters has been proposed. Quantitative calculations of the necessary yaw rates need to be made to determine the usefulness of this control and whether or not it is compatible with the guidance system.

A third possibility, although remote, involves positioning one astronaut within the LEM prior to lunar launch such as to shift the center of gravity. The shift would effectively develop a torque to offset a torque loss due to a failed thruster.

<u>RCS Failure Detection System Status</u>

The critical nature of a single thruster failure has been known for some time and has been a prime cause behind proposals to include a failure detection system in the LEM. On July 9, 1965, Grumman was given direction by TWX to proceed with implementation of such a system. A review of documentation associated with the problem of RCS failures and their detection shows that considerable discussion between MSC and GAEC and within MSC during the past year concerned the type of thruster failure sensor to be used: pressure sensors as opposed to force sensors. Objections to the use of pressure transducers have been raised based primarily on reliability considerations tempered by operational experience. There appears to be general agreement that sensors are not required on all propellant lines (as originally proposed) since this would only assist in leak isolation which can be accomplished with an insignificant increase in operational procedures.

The direction from ASPO to GAEC stipulated the removal of the propellant line transducers and the use of force sensors as opposed to pressure sensors. The development of the force transducer is now in progress at MSC.

It is interesting to note that preliminary on-board instrumentation and telemetry requirements for failure analysis of the LEM RCS system on the ground have been documented. The supposition was that such instrumentation would be necessary if an on-board detection system were not included.

Conclusions

(1) The action item statement that failure of one LEM RCS thruster could require mission abort has been confirmed.

(2) MSC has recognized this problem and is presently implementing a failure detection system for the LEM RCS system. The detection system will not alleviate the problem but will provide a means for timely corrective action.

(3) A review of other Apollo Program reaction control systems should be conducted to determine any other requirement for failure detection systems.

Acknowledgments

Contributions to the information contained in this memorandum were made by personnel at MSC in the Engineering Division (ASPO), Guidance and Control Division (E&D), Astronaut Office and Flight Crew Support Division (Flight Crew Operations), Flight Control Division, and Mission Planning and Analysis Division (Flight Operations). Their assistance in this study is appreciated.

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2031-RRS-pas

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Attachments
Table I and Figure I
References

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(see next page)

Copy to (Complete Memorandum)
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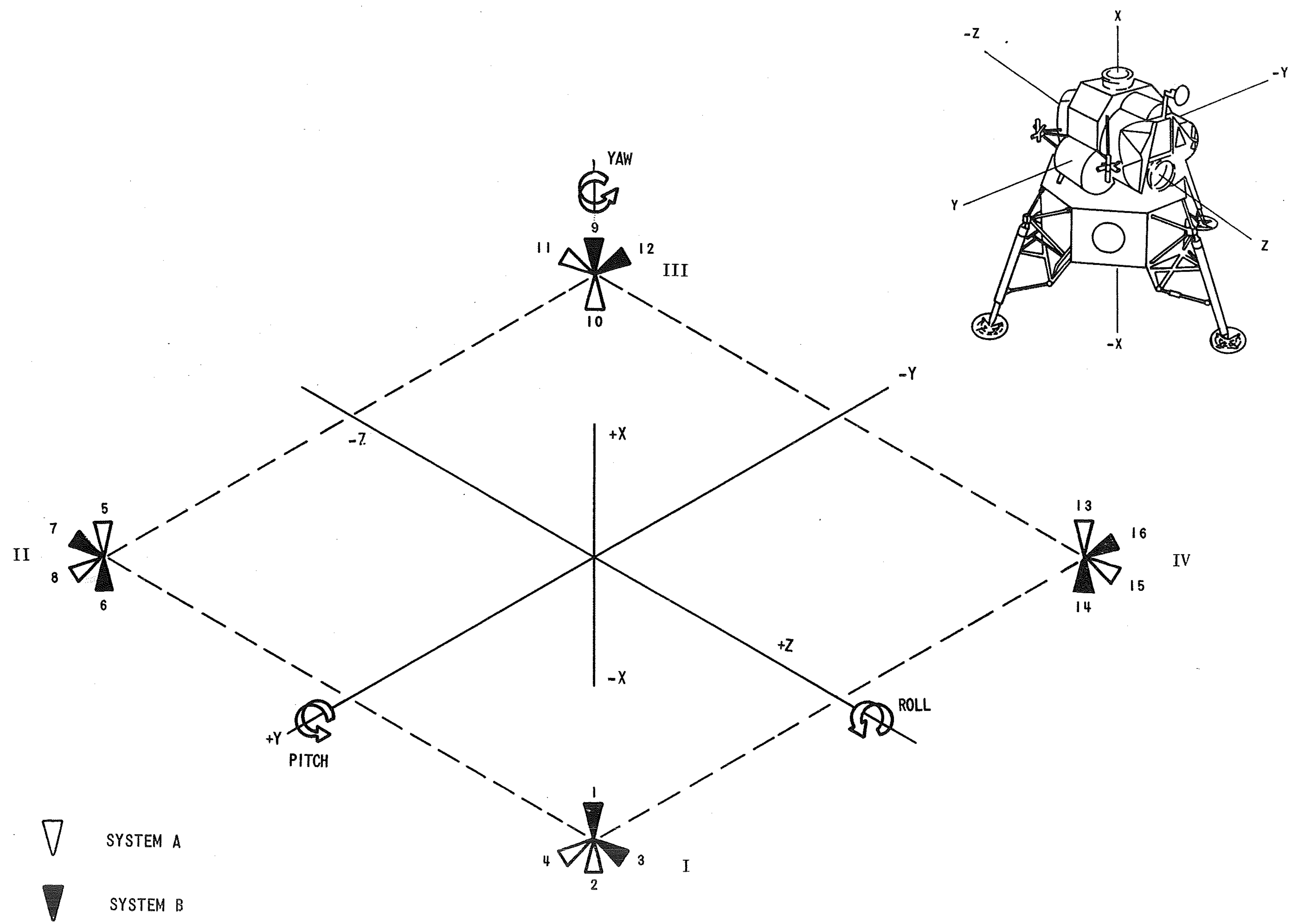

LEM RCS THRUSTER ORIENTATION
FIGURE 1

TABLE 1 LEM RCS THRUSTER UTILIZATION MATRIX

THRUSTER NO. SYS A: ○ SYS B: ● THRUSTER AXIS		1 X	2 X	3 Z	4 Y	5 X	6 X	7 Z	8 Y	9 X	10 X	11 Z	12 Y	13 X	14 X	15 Z	16 Y	NUMBER IN SYS A ○	SYS B ●	TOTAL THRUSTERS	CRITICAL MOTIONS (NOTE 1)
TRANSLATION																					
X	+		○				●				○				●			2	2	4	
	−	●				○				●				○				2	2	4	
Y	+												●				●		2	2	✓
	−				○				○									2		2	✓
Z	+							●				○						1	1	2	✓
	−			●												○		1	1	2	✓
DIAGONAL AXES (NOTE 2)																					
A RIGHT FRONT - LEFT REAR	+							●				○	●				●	1	3	4	
	−			●	○				○							○		3	1	4	
B LEFT FRONT - RIGHT REAR	+			●									●			○	●	1	3	4	
	−				○			●	○			○						3	1	4	
ROTATION																					
YAW	LEFT				○			●					●			○		2	2	4	
	RIGHT			●					○			○					●	2	2	4	
PITCH	UP		○			○				●					●			2	2	4	
	DOWN	●					●				○			○				2	2	4	
ROLL	CLOCKWISE	●				○					○				●			2	2	4	
	COUNTERCLOCKWISE		○				●			●				○				2	2	4	
DIAGONAL AXES (NOTE 2)																					
C RIGHT FRONT - LEFT REAR	+					○									●			1	1	2	✓
	−						●							○				1	1	2	✓
D LEFT FRONT - RIGHT REAR	+		○							●								1	1	2	✓
	−	●									○							1	1	2	✓

NOTE 1 LOSS OF ONE JET IS CRITICAL IF THE LOSS OF A SECOND JET CAN RESULT IN LOSS OF CONTROL ABOUT AN AXIS.

NOTE 2 A QUAD I THROUGH QUAD III

B QUAD II THROUGH QUAD IV

C QUAD I THROUGH QUAD III

D QUAD II THROUGH QUAD IV

SEE FIGURE 1 FOR QUAD NUMBER DESIGNATION

REFERENCES

1. Paragraph 3.1.3.3.2, "Apollo Program Specification", May 1965.
2. "LEM and Space Suit Assembly Contingency Analyses", Grumman Aeronautical Engineering Corporation AMPTF Report No. 540-13, October 26, 1964.
3. "Mission Related Design Requirements for the LEM Reaction Control Subsystem", Grumman Aeronautical Engineering Corporation, AMPTF, Report No. LED-540-24, October 26, 1964.
4. LEM Mass Property Report, LED-490-20, May 1, 1965.